Uraizee F and Narsimhan G (1996) Effects of kinetics of adsorption and coalescence on continuous foam concentration of proteins: Comparison of experimental results with model predictions. *Biotechnology and Bioengineering* 51: 384.

Weijenberg DC, Mulder JJ, Drinkenburg AAH and Stemerding S (1978) The recovery of protein from potato juice waste water by foam separation. *Journal of Engineering and Chemical Processing, Design and Development* 17: 209.

Froth Processes and the Design of Column Flotation Cells

I. M. Flint, Canadian Process Technologies Inc., Vancouver, BC, Canada
M. A. Burstein, NPACI Edcenter on Computational Science and Engineering, San Diego State University, San Diego, CA, USA

Copyright © 2000 Academic Press

Introduction

The function of a flotation column is selectively to separate certain suspended solid particles or liquid droplets based on their surface properties. Bubbles rise and particles (drops) settle within the vessel, and collisions are highly dependent on gravitational momentum. The vessel is a multiphase contacting/heterocoagulation device where the dispersed phase to be removed attaches to the bubbles and accumulates at the top of the column in the form of froth. The latter overflows to launders. In this quiescent system, transport, dispersion and mixing of materials are induced by the motion of gas bubbles in the continuous liquid medium.

For the purpose of designing columns, immiscible liquid droplets are considered as acting as solid spheres of an appropriate size and density: thus, a 'particle' may represent either a solid or a liquid.

Almost all flotation columns are operated in the countercurrent regime where slurry moves downwards against a continuous rising bubble swarm. This type of flow increases efficiency (selectivity) of separation as the distance between discharge ports for overflow and underflow is large. In some cases, for example for the flotation of very coarse particles, co-current columns can be considered in order to increase particle residence time and reduce loaded bubble rise time. Unless otherwise stated, all of this article is related to countercurrent columns.

Initial Design Data

The feed transport fluid must be characterized in terms of liquid flow rate and chemical composition. Component solids or immiscible liquid flow rate, material composition and size distribution must also be known. In all cases, mean values, standard deviations and design maxima and minima are required.

Test work must be done, or approximations made, to determine the flotation characteristics of the material to be separated, including rate constants and maximum recovery for all material and particle (droplet) size fractions. Process targets must be well understood, including the desired quality of products and recovery. Data error must be minimized since it directly impacts on the accuracy of the design scale-up.

Site-specific information is also required for final designs. This includes limitations in dimensions due to plant layout, civil engineering specifications, including such items as wind loading, earthquake considerations, supporting platforms and others.

DropBooks

General Dimensions

Typically, columns range in height from 6 to 15 m. This height is dictated by the dimensions of the different zones within the column but is most influenced by the collection zone height.

Column cross-sections are usually round or rectangular. Cylindrical columns do not have special flow conditions at the corners. They, therefore, usually have a more uniform air and feed distribution, less tank weight due to the self-supporting nature of the structure and less wall area per unit operating volume. Rectangular columns use floor space more efficiently and are easier to baffle. The cross-sectional area is usually constant throughout the vessel and is determined by carrying capacity and residence time considerations in the collection and froth zones. Typical industrial cell cross-sectional areas range from less than 1 m^2 to more than 12 m^2.

Column Zones

The flotation column, as generally built, is composed of a number of distinct zones. Under the spargers there is a dead volume (underflow zone) which is only used to remove slurry from the vessel. The volume between the spargers and the feed port is called the collection zone. The volume between the feed port

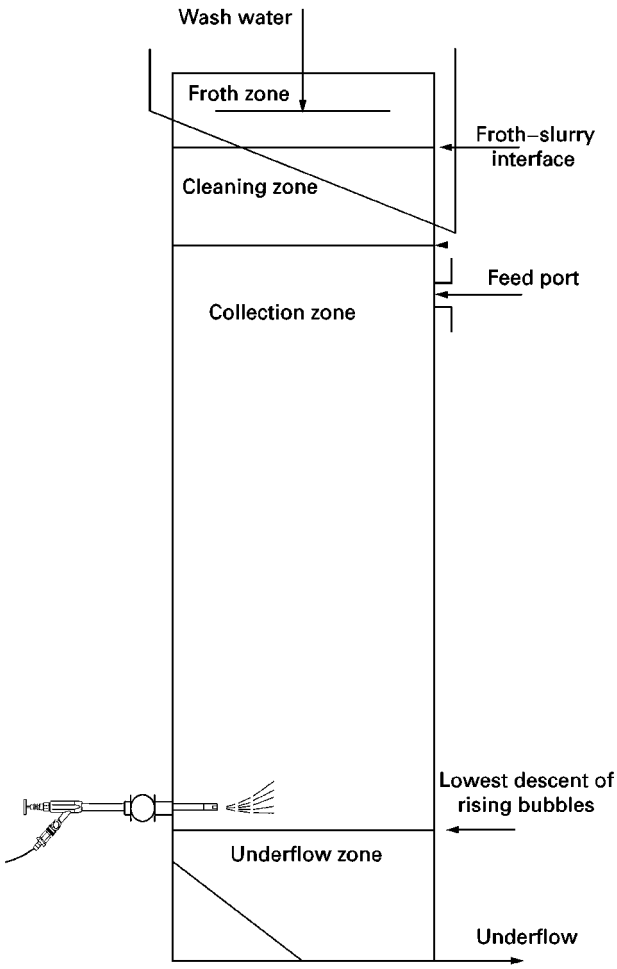

Figure 1 Column hydrodynamic zone.

and the froth interface is called the cleaning (recollection) zone and above the interface is the froth zone. The froth zone may be further divided into the washing zone, if it is under the wash water distributor, and the free drainage zone, if it is above. These zones are illustrated in **Figure 1**.

Underflow Zone

The physical dimensions of this zone should be minimized since its roles are to ensure that there are no small bubbles entrained by the downward flow to the underflow stream, that sloughing of the solids particles does not occur, and that the outflow from the base of the column does not create unwanted flow patterns within the active zones of the vessel. Bubble entrainment to the underflow is obvious, as in this case frothing occurs in the tailing sump or in the next open tank downstream of the column.

A zone underneath the spargers does not contribute to the floatation collection or separation. Design considerations of the zone include base cone angle and placement, underflow exit port configuration and height to spargers.

Base Cone Design

In most solids separation applications, the base can be designed flat. The solids will eventually form a false bottom at the angle of repose under the specific flow conditions. Depth of the base cone should be selected considering angle of repose of particles. If sloughing of solids is considered a problem, then the column can be designed with either a real or false bottom at an angle greater than the angle of repose.

Underflow Port

Generally, the output port is designed to pull from the cross-sectional centre at the base of the vessel in order to minimize both the flow differences within the collection zone and large scale slurry circulation patterns.

The spargers are placed at a level such that the furthest descent of bubbles is above the highest expected solids settling point.

Collection Zone

The collection zone is characterized by a stream of individual bubbles rising against a descending liquid or slurry. This is the zone in which the bubble–particle attachment occurs. The capacity of the column is dictated in part by the intensity of bubble–particle collision (number of collisions per unit time), the probability of attachment, and the bubble surface area flux through the vessel (removal ability) in this zone.

When sizing a column, certain assumptions are made. These include that the column operates with dispersed bubbles that rise as a swarm without slugs. It is also assumed that the flow of bubbles, liquid and solids is uniform across the column, and that there are no large scale vortices.

There are four main collection zone design criteria which determine the vessel dimensions: floatable particle residence time, mixing characteristics, maximum gas rate and bubble loading. The resulting volume can usually be achieved with a range of height-to-diameter options. The final dimensions are also dictated by layout and economic considerations. It should be emphasized that this zone must be designed in parallel with the sparging system and froth zone as each of these parts influences the others. The placement of the column within the

operating circuit will also impact on the final design and operation.

Solids Settling

Particles settle within the column system since there is no mechanical agitation to suspend them. As such, each particle will have a specific hindered settling velocity dependent on size, density of the particle and the effective density and viscosity of the suspension with modifications due to bubble-induced mixing. Mixing enhances particle suspension, so small and/or light particles do not have their own trajectory and follow liquid flow more than in two-phase systems. The settling velocity generally has little influence on residence time for particles smaller than about 20 μm, but becomes an important design condition for larger particles.

Particle Residence Time Distribution (RTD)

Material residence time depends upon the inherent mineral settling velocity under the conditions within the column and the superficial velocity of the slurry. The total collection zone height divided by the summation of the hindered settling and slurry velocities gives a total average residence time for each particle size and density. More precisely, the particle residence time is a stochastic parameter influenced by the turbulent mixing and potential macrocirculation patterns within the column.

Elementary Processes

Flotation depends on the elementary processes of collision and attachment. In columns the probability of collision between a particle and a bubble remains virtually constant within the collection zone. There is a higher probability of attachment at the bottom of a countercurrent column since bubble surface coverage by particles is low for newly formed bubbles. This maximizes the recovery of the small proportion of particles targeted for flotation that are still present in the lower parts of the zone.

The relative movement of slurry and rising bubbles is the main source of mixing energy in columns. This results in a low intensity of the turbulence (low energy dissipation and large internal scale of turbulence) and, therefore, low relative bubble–particle velocities and accelerations. Bubble–particle collision efficiency is due to gravitational and inertial particle drift from the liquid streamlines around the rising bubble and due to the interception. The probability of particle detachment from bubbles is limited since the velocity gradient around the bubble is minimized.

Rate Constant

The floating ability of a material is generally referred to as a rate constant, similar to chemical processes, and is assumed (for simplicity) to be of first-order kinetics for each mineral component and size fraction. The value of this term is dependent on a complex function involving the collision/attachment and detachment, as well as processes occurring in other zones of the flotation column (see below). These data are generally determined through test work. As mechanism and intensities of subprocesses (collision, attachment, detachment, entrainment) in column and impeller flotation can be substantially different, the lab and pilot tests for column design and scale-up should also be made in columns. First-order flotation rates for the components can be determined from the recoveries in a continuous lab flotation column, or by simulation of kinetic tests by recycling column tails back to the feed line.

Taking into consideration separate first-order kinetic models for individual subprocesses and taking into account free bubble surface reduction in the upward direction would lead to complicated nonlinear kinetic equations. These are important in understanding the physics of the process, but cannot be used for scale-up or control, due to unavoidably high error in determining their coefficients from experimental data.

DropBooks

Carrying Capacity

The removal capability of the bubbles is called the carrying capacity and is the general term which characterizes the maximum amount of solids carried by the air bubbles (either in reference to the maximum capacity of the column, or to the maximum capacity per air volume). This refers to the fact that only a specific amount of particles can be attached to and removed by a certain bubble area. Thus, the maximum floatable solids removal or the surface area of attached particles is related to bubble surface area flux.

Typically, the distance between spargers and the slurry–froth interface is between 6 and 12 m. This leads to a substantial mass of particles attached to a bubble (bubble loading).

As bubbles become loaded by collected particles, the contact time between particle and bubble reduces due to the shortening of particle trajectory along the free bubble surface. This means that the rate of collection slows as loading increases, especially when the lower section of a bubble is virtually covered by attached particles. Detachment probability is also much higher for particles attached to the upper hemisphere of a bubble.

Smaller bubbles can carry more solids than larger bubbles, assuming an equal gas rate and that the loaded bubbles have sufficient buoyancy to move against slurry flow. A smaller weight of fine particles can be carried at a constant gas rate and bubble size distribution than that of coarse particles.

Carrying capacity limitations should be taken into account when estimating height-to-diameter ratio for columns working at high overflow (froth) yield. Typical carrying capacity per unit column cross-sectional area for base metal minerals flotation is 2.5 t/(m^2 h) and for coal flotation 1.5 t/(m^2 h).

Gas Rate and Bubble Size

Column cells are operated in the bubbly region where bubbles rise in a swarm. The flow regime in the column may change to the 'churn-turbulent' condition when coalescence is caused by gas entering a region faster than it can leave as small bubbles. As smaller bubbles have lower swarm rising velocity, the flooding occurs at a lower gas rate for fine bubble dispersions. Thus, there is a link between maximum gas rate at the flooding point and bubble size. Also, flooding is enhanced by countercurrent slurry flow; the higher its superficial velocity, the lower the gas rate at the flooding point. At bubble size ranges used for column flotation, flooding occurs typically at a superficial air velocity of 2.5–3 cm s^{-1}. More precise values can be calculated from the drift flux model.

It is also possible for uniform countercurrent froth flow to occur in the column even at lower superficial air and slurry rates when the bubbles are very stable (gas hold-up at both bubble and froth flow regimes can also be estimated based on the drift flux model).

Mixing

Columns are commonly sized with a dispersion method which uses the Peclet number, a dimensionless criterion, to characterize mixing. It is assumed that an axial dispersion model adequately reflects flow structure in the collection zone. It is also possible to use a tanks-in-series flow model. The Peclet number reflects the ratio between the downward path of particle and the average length of its stochastic drift due to mixing (diffusion). It is equal to UL/D, where U is the mean velocity of the phase of interest (for particles it is the sum of downward liquid velocity and a hindered settling velocity), L is the characteristic length scale for the apparatus (collection zone height of the column), and D is the turbulent dispersion (diffusion) coefficient. The latter can be determined by a tracer technique or by using one of several approximation formulae. D ranges from 0, for perfectly mixed systems, to infinity, for plug flow. The following variables have an effect on the Peclet number: bubble size and number of bubbles (which are dependent on gas rate and surface tension), slurry rate, particle settling velocity, collection zone height and diameter. At a constant collection zone volume, a taller column is better from a flow structure perspective as less mixing is induced. Peclet number can be estimated using one of the experimental relationships, or from particle residence time distribution (RTD) similar to that in chemical reactors or separation equipment. RTD can be directly measured using a tracer method. Dispersion of the RTD can be used to calculate turbulent diffusion D and other column flow structure criteria.

The absence of an agitator limits the formation of large scale flow loops unless the column is operated in a high air rate, churn-turbulent flow or the feed distribution of either air or slurry is not even. Low mixing intensity and lack of circulation contours cause particle residence times to be highly dependent on the particle settling velocity. Reduced mixing leads to lowering of local upward flow intensities which minimizes particle entrainment to the froth. Thus, at a constant collection zone volume (slurry retention time), its increased height leads to lower mixing intensity and improved (due to this) metallurgical results up to the point when restrictions in carrying capacity limits concentrate (float product) yield. Also, higher superficial slurry velocity reduces negative influence of mixing and slime entrainment intensity.

Careful design and positioning of any baffles (horizontal or vertical), the feed system, and any internal piping that may be needed minimize local turbulence. The feed pipe must be located high enough in the column to maximize the collection zone length but also low enough to limit turbulence at the slurry–froth interface.

Entrainment

Fine and/or light hydrophilic particles may pass upwards through the collection zone by entrainment. There are two forms of entrainment. In the first, a portion of feed water containing suspended fine particles passes into the froth. This type of entrainment can be minimized by maintaining a net downward flow of water through the upper column zones. The second form of entrainment is the capture of particles in the eddies behind a rising bubble. These particles are also rejected in the froth zone operating with positive bias.

Baffling

Columns may be vertically baffled in order, both to reduce mixing and to lend additional structural support. An important condition to achieve effective operation with a baffled column is an even feed and air distribution between the compartments, otherwise detrimental circulation patterns may form between the baffled sections. This overall circulation can make a baffled column less effective in terms of flow structure than a column without baffles. Normally, baffles are installed above and below the feed distributor in a column, leaving space around feed pipe(s) and air spargers open to allow even distribution of the slurry and air bubbles, respectively.

Horizontal baffles (plates) are not typically used, though tests have confirmed their ability to improve flotation of coarse particles due to less short-circuiting in the wall part of the baffled column.

Physical Dimensions

The total volume of the collection zone is determined by residence time considerations, having also accounted for mixing and hindered settling of coarse particles, to achieve target recoveries. A formula based on an axial dispersion model and first-order flotation kinetics is typically used. A minimum diameter is then calculated to allow sufficient bubble surface area to float the required solids. The diameter and height must be larger than these minimum numbers and any combination can be used as long as the volume remains above its minimum. The volume should provide for the necessary retention time with a correction for mixing, but should not exceed it substantially. This is critical in the case of selective flotation when both components are floatable and have different but nonzero rate constants.

The selection of the vessel dimensions is an iterative process since a change in many of the variables will change the overall mixing in the vessel.

Access

Periodic maintenance is required, and access to the inside of the column may be needed. Therefore, access manholes and appropriate clearances must be maintained within the vessel.

Cleaning Zone

The purpose of this zone is to buffer the froth zone from the turbulence of the feed port. It is located above the feed port and below the interface with the froth. It is characterized by rising bubbles that may be highly loaded with solids rising from the collection zone and falling solids that have been entrained in the bubbles' wake, or have been rejected in the froth zone by loss of bubble surface area. If a sufficient amount of wash water is used, this zone may have a net downward flow of slurry. Only a limited number of previously uncollected particles occurs in this zone due to the turbulent mixing or entrainment. Since collection of these particles can also occur in the collection zone, the height of the cleaning zone should be minimized but must be sufficient to allow damping of the feed turbulence below the froth interface.

In some circumstances the cleaning zone is the overflow point of the float product. This occurs when there is no froth zone either because a froth cannot be maintained in a solids float, or because a liquid–liquid separation is being performed. In the latter case an organic pad may be present.

Froth Zone

This zone is usually present in solid–solid or solid–liquid separations.

The froth zone in a column cell is characterized by a rising bed containing a matrix of bubbles, which are loaded with hydrophobic material, water lamellae between bubbles and Plateau–Gibbs canals. Entrained hydrophilic material may be found initially either in lamellae or in canals. Film (lamella) thinning and bubble coalescence in froth (syneresis) and drainage in Plateau–Gibbs canals are the main mechanisms of gas hold-up increase and concentrate upgrading with height in the froth. This is caused by reduction of the air–liquid interface area and subsequent particle detachment. Tracer tests indicate that, in some cases, more upgrading is observed within the froth than between slurry and lower froth layers.

Quiescent conditions in columns create a stable froth that allows the addition of wash water. This water displaces the liquid phase of the feed slurry, with entrained associated fine particles, from the froth lamellae and Plateau–Gibbs canals and allows the production of an essentially entrainment-free overflow. In some cases, addition of small amounts of water into the froth also improves the stability and rheological properties of the countercurrent froth.

A presence of highly hydrophobic, angular particles large enough to bridge the lamella between bubbles, without a population of smaller hydrophilic particles, causes froth destabilization. In this case the froth zone design is critical. In extreme cases a froth bed may not be possible.

Channelling

Uneven distribution or excessive addition of wash water can cause formation of channels in the froth

DropBooks

and possible froth collapse. Care must be taken in the design of the distributor to ensure even cross-sectional wash water flows.

Froth Zone Dimensions

Although the froth zone usually has the same cross-sectional area as the collection zone, it may be necked to promote crowding which increases the upward velocity in the froth. This may be done when small amounts of froth are generated, reagent conditions dictate that the froth will not be stable, or the size distribution of solid particles in the froth promotes coalescence of bubbles. It is more common to preserve the overall area and apply internal baffling and launders. Internal baffles may be added to support the froth, or to contain or localize froth collapse.

Internal Launders

Syneresis and coalescence occur within the froth zone. Thus, relative to a localized section of froth, bubble surface area is lost with time as that section travels from the slurry–froth interface to the overflow points. Furthermore, analysis of particle RTD in froth indicates that horizontal transport to the froth launder is very slow. For larger diameter columns, dead zones can form in the central part of the vessel. Columns normally do not have froth skimmers or paddles. Therefore, fast froth removal is critically important for operation and is often achieved by a series of internal froth launders.

Organic Pad

Liquid–liquid column applications may be operated with an organic pad on the top of the vessel. Organics floated in the collection zone gather at the surface of the vessel. These may overflow a weir continuously if the organics concentration is sufficient or if low concentrations of organics in the overflow stream are acceptable. Otherwise, the pad accumulates and is dumped on a regular basis. If some or all of the organic compounds present in the system are volatile, a pad may not be suitable or dumping must be frequent to prevent excessive stripping.

Air-Sparging Systems

The purpose of the sparging system is to distribute evenly the appropriate-sized bubbles near the bottom of the column. The sparging system is critical and must be designed taking into consideration many elements, including bubble size distribution, maximum air rate, bubble coalescence and induced mixing; uniformity of air hold-up across the vessel, minimization of scale formation, resistance to wear, required air pressure and maintenance considerations.

There are many types of spargers used in column cells. Pneumatic (porous media or perforated) spargers form bubbles at small orifices. Pneumohydraulic spargers break up an air stream into bubbles by a water jet as an air-water mixture is distributed into the column. The air jet spargers form bubbles through the high velocity injection of air into the column. There are also a class of spargers termed external spargers that aerate the feed slurry, or portion of the underflow, and use the column as a de-aeration or bubble separation vessel rather than for particle collection. Combination of external spargers for slurry pre-aeration with microbubbles and/or dissolved air with internal spargers to facilitate microbubble buoyancy by adding larger bubbles is optimal for a wide range of applications (see below). In recent years, the general trend among major column suppliers is to use air jet and external types of spargers, although specific circumstances dictate the use of other types.

Care must be taken when designing the bubble distribution system to ensure that an even flow of bubbles is generated. Poor air distribution can cause large scale flow patterns in the column that are detrimental to performance. Macrocirculation zones can also be caused by a misalignment of the column either by bows along the length or by offsets from the vertical.

Pre-Aeration

Columns, by nature, have low turbulent momentum between the bubbles and particles, meaning that smaller particles have slow flotation kinetics in these vessels. The column is, however, a good separator of bubbles from the feed slurry, especially if wash water is added. This feature virtually eliminates hydrophilic entrainment. In order to improve the collection of fine particles, a pre-aeration system or intense flotation device can be used. These devices act by creating a turbulent zone, where the inertial momentum of both bubbles and particles is high (due to high intensity turbulence and velocity gradients) enabling higher recovery of the smallest floatable particles by microbubbles. If the pressure in the pre-aeration device is substantial, a portion of air is dissolved and then released in a column; normally, nucleation of air bubbles occurs at a solid surface, thus a collision stage of flotation process is eliminated for the cavitation bubbles.

Pre-aeration devices then feed a modified column which acts as a recollection device for the larger particles and a bubble coalescence/separation system.

Civil Engineering and Material of Construction

The final column design must be site-specific. There may be height and/or area considerations due to restrictions of space, and weight and loading considerations due to foundation requirements. In addition, some environmental considerations such as wind load, earthquake zone and rainfall intensity will affect steel thickness, foundations and attachments, braces and access platforms. As columns are normally much taller than mechanical flotation cells, they are often located outside, and these factors can play an important role in column design. There are also process considerations like per cent solids, wear factors, chemical composition of the slurry (pH, etc.) and particle size distribution which affect the physical structure, pipe sizing and materials of construction. In special cases, these units may be designed as pressurized vessels or as enclosed systems.

For example, many oil–water separation columns are pressurized or some installations use circulating inert gases to minimize oxidation. When columns are installed for oil–water separation duties, mainly on offshore platforms, a circulating hydrocarbon gas (propane) is often used instead of air.

Conclusions

Despite its simple design, the scale-up and modelling of column flotation is a complex problem. It includes analysis of three-phase three-dimensional flow in collection and cleaning zones and in the washed thick froth layer. In the last few years, a technique for column design has been developed. Its adequacy has been confirmed by many columns installed worldwide for a wide range of mineral and other applications.

Special attention should be paid to the carrying capacity of air bubbles and to secondary upgrading in the froth.

Design of air-sparging systems, feed distributors and also froth discharge systems is critically important for successful column operation.

Unconventional design and use of pre-aeration systems are the main trends in flotation column development at present.

See also: **II/Flotation:** Column Cells.

Further Reading

Clift R, Grace JR and Weber ME (1987) *Bubbles Drops and Particles*. New York: Academic Press.

Dobby GS and Finch JA (1986) Flotation column scale-up and modelling. *CIM Bulletin* 79: 89–96.

Finch JA and Dobby GS (1990) *Column Flotation*. Oxford: Pergamon.

Levenspiel O (1972) *Chemical Reaction Engineering*. 2nd edn. New York: Wiley.

Lynch AJ, Johnson NW, Manlapig EV and Thorne CG (1981) *Mineral and Coal Flotation Circuits, Their Simulation and Control*. New York: Elsevier.

Masliyah JH (1979) Hindered settling in a multi-species particle system. *Chemical Engineering Science* 34: 1166–1168.

Ross VE and van Deventer JSJ (1988) Mass transport in flotation column froths. *Column Flotation '88. Proceedings of the International Symposium*, Phoenix, Arizona. Littleton, Colorado: Society of Mining Engineers.

Rubinstein JB (1995) *Column Flotation, Processes, Designs and Practices*. Basel: Gordon and Breach.

Schuhmann R. (1942) Flotation kinetics 1: methods for steady state study of flotation process. *Journal of Physical Chemistry* 46: 891–902.

Zhou ZA, Xu Z and Finch JA (1994) On the role of cavitation in particle collection during flotation – a critical review. *Mineral Engineering* 7: 1073–1084.

DropBooks

Historical Development

Z. Xu, University of Alberta, Edmonton, Alberta, Canada

Copyright © 2000 Academic Press

Flotation is a versatile, surface wettability-based separation process, usually taking place in an aqueous medium. In flotation, a water-repellent (hydrophobic) target to be separated is attached to a carrier lighter than the medium in which separation occurs. The target varies from fine particulates (solid or liquid) to ions and molecules, while the most commonly used carriers are air bubbles due to their ready availability, easy handling and very low cost. Compared to other light fluids (e.g. paraffin oil), air has the highest hydrophobicity, and its low density facilitates mass transfer of bubble-target aggregates from the bulk medium to the interface where froth forms and is collected/removed. Flotation was practised around a century ago, mainly for mineral separation applications. It is difficult, if not impossible, to pin down who should be given credit for the